Review of Particulate Matter and Elemental Composition of Aerosols at Selected Locations in Nigeria from 1985-2015

Ifeanyi F Offor,[1] Gilbert U. Adie,[2] Godson REE Ana[3]

1 Department of Chemistry, Faculty of Science, Federal University, Ndufu Alike, Ikwo, Nigeria
2 Department of Chemistry, Faculty of Science, University of Ibadan, Ibadan, Nigeria
3 Department of Environmental Health, Faculty of Public Health, College of Medicine, University of Ibadan, Ibadan, Nigeria

Corresponding Author:
Ifeanyi F. Offor
Department of Chemistry, Federal University, Ndufu-Alike, Ikwo Nigeria
Tel. +234(0) 8054691849
offorifeanyi@gmail.com

Background. Over the past 30 years, various studies in Nigeria have monitored atmospheric particulate matter loads and elemental composition of ambient air around diverse receptor sites.
Objectives. A comparative discussion of the different sampling techniques, pre-treatment and analytical methods employed between 1985 and 2015.
Methods. Air pollution indices from studies covered in this review were compared to relevant guideline standards such as the World Health Organization (WHO) 24-hr guideline and the United States Environmental Protection Agency (USEPA)'s National Ambient Air Quality Standard (NAAQS) daily permissible limits for fine particles of less than 2.5 micrometers in diameter ($PM_{2.5}$) and coarse dust particles with a diameter of 10 micrometers (PM_{10}) in ambient air. In addition, the sources of data for the average concentrations for $PM_{2.5}$, PM_{10} and related metallic elements during 1985-2015 were assessed. Attempts were also made to compare varied particulate matter loads of atmospheric micro-environments in Nigeria with comparable micro-environments in selected cities around the world.
Discussion. Results showed that $PM_{2.5}$ concentration ranged from 5-248 μg/m^3, while PM_{10} concentration ranged from 18-926 μg/m^3, revealing that about 50% of the particulate matter loads in Nigeria exceeded both the WHO (25 μg /m^3, 50 μg/m^3) and NAAQS (35 μg/m^3, 150 μg/m^3) guideline limits for $PM_{2.5}$ and PM_{10} respectively. $PM_{2.5}/PM_{10}$ ratios for the selected studies fall below the WHO guideline (0.5-0.8), suggesting that Nigerian aerosols are mainly made up of coarse, rather than fine particles. In addition, the order of the average highest concentrations of metallic elements for $PM_{2.5}$ were magnesium (Mg) > strontium (Sr) > potassium (K) > zinc (Zn) > iron (Fe) > sodium (Na) > aluminium (Al) > chlorine (Cl) > lead (Pb) > silicon (Si), while those of PM_{10} were Sr > Zn > Fe > Mg > calcium (Ca) >Na > Pb > manganese (Mn) > K > Al.
Conclusions. Seasonal variation of particulate matter loads revealed higher concentrations during the dry season than during the rainy season. In addition, particulate matter loads in rural areas were generally lower than in urban areas. Wind-blown dust from the Sahara Desert is the major contributor to particulate matter loads in northern zones of the country, while sea spray and crustal matter are the highest contributors to particulate matter loads in southern zones.
Competing Interests. The authors declare no competing financial interests.
Keywords. Particulate matter, Composition, Pollution, Source apportionment
J Health Pollution 10: 1–18 (2016)

Introduction

Particulate matter is the term given to the tiny particles of solid or semi-solid material found in the atmosphere as suspended mixtures. The chemical complexity of airborne particles makes it imperative to consider the composition and sources of selected primary and secondary particulates deemed to be of health concern. Primary particulates are introduced into the atmosphere from a variety of natural and anthropogenic sources. Secondary particulates tend to form in the atmosphere as a result of chemical processes.[1,2] Urban particulate pollution has been recognised as a major problem in emerging mega-cities in Nigeria such as Lagos, Kano, Abuja, Aba and Port-Harcourt as a result of their rising populations and increasing urban infrastructures. In addition, the West African sub-region where Nigeria is located falls within the intensively burdened aerosol regions as a result of trans-boundary movements of geogenic particles from desert zones of the Sahara and soot/organic carbon load from biomass burning.[3] Furthermore, emissions from vehicular traffic and smelting industries, as well as dust from unpaved roads also contribute to the aerosol load, especially in the dry season months. Thus, atmospheric particulate matter is an important air quality indicator, because it not only has a direct impact on human health, it also plays a role in atmospheric chemistry, weather, and climate.[4]

Many epidemiological studies have revealed consistent associations between ambient concentrations of particulate matter with an average diameter of 10 micrometers (PM_{10}) and fine particles of less than less than 2.5 micrometers in diameter ($PM_{2.5}$) with adverse health effects such as cough, asthma, renal failure, and infertility.[5,6] Detailed understanding of the concentration levels of important air pollutants like $PM_{2.5}$ and PM_{10}, polychlorinated biphenyls, dibenzo-p-dioxins/dibenzofurans and polycyclic aromatic hydrocarbons in urban and rural areas of the country have remained largely unknown.[7] Although there have been some pioneer studies on $PM_{2.5}$ and PM_{10} concentrations and source contributions of different urban sources to the ambient air pollution at selected receptor sites in Nigeria, polycyclic aromatic hydrocarbons, dibenzo-p-dioxins/dibenzofurans and polychlorinated biphenyls have yet to be extensively studied. Between 1988 and 1994, segregated studies involving documented contributions of pollutant sources in Nigerian sectorial and national emission inventories were surveyed by a research team.[3,8] In the area of particulate matter levels ($PM_{2.5}$, PM_{10}), segmented studies involving selected receptor sites in Lagos and Abuja have been carried out over the years.[7,10-16] In addition, a more extensive study involving six Nigerian mega-cities was undertaken.[17] Furthermore, a sampling campaign of particulate matter load ($PM_{2.5}$, PM_{10}) in ten selected south-eastern Nigerian cities during dry and wet season periods (December 2008 to September 2009) was also undertaken.[18]

In addition, a monitoring study of ambient particulate matter (PM_{10}) spatial distribution in 17 selected cities in Nigeria over a six year (2001-2006) period and the resultant health

Abbreviations

Ag	Silver
Al	Aluminum
As	Arsenic
Ba	Barium
Bi	Bismuth
Br	Bromine
Ca	Calcium
Cd	Cadmium
Ce	Cerium
Cl	Chlorine
Co	Cobalt
Cr	Chromium
Cs	Cesium
Cu	Copper
EC	Elemental carbon
EDXRF	Energy dispersive X-ray fluorescence
Fe	Iron
Ga	Gallium
Hg	Mercury
INAA	Instrumental neutron activation analysis
K	Potassium
La	Lanthanum
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Na	Sodium
NAAQS	National Ambient Air Quality Standard
NH_3	Ammonia
NH_{4+}	Ammonium
Ni	Nickel
NO_3	Nitrate
OC	Organic carbon
P	Phosphorus
Pb	Lead
PCFA	Principal component factor analysis
PIXE	Proton-induced X-ray emission
$PM_{2.5}$	Particulate matter less than 2.5 micrometers in diameter
PM_{10}	Particulate matter with an average diameter of 10 micrometers
PMF	Positive matrix factorization
Rb	Rubidium
S	Sulfur
Sb	Antimony
Sc	Scandium
Se	Selenium
Si	Silicon
Sm	Samarium
Sn	Tin
SO_4^{2-}	Sulfate
Sr	Strontium
Ta	Tantalum
Th	Thorium
Ti	Titanium
USEPA	United States Environmental Protection Agency
V	Vanadium
WHO	World Health Organization
Zn	Zinc
Zr	Zirconium

Study location(s)	$PM_{2.5}$ Mean (μg/m³)	$PM_{2.5}$ Range	PM_{10} Mean (μg/m³)	PM_{10} Range	Average Ratio $PM_{2.5}/PM_{10}$
Aba[18, 21]	46.90	5-248	302.58	18-975	0.16
Umuahia[18]	40.06	4-140	273.85	51-911	0.15
Nnewi	23.53	1-68	56.97	21-122	0.41
Onitsha[18]	66.10	4-188	593.7	95-1600	0.11
Abakaliki	28.13	2-72	87.57	29-158	0.32
Afikpo[18]	25.32	1-64	71.75	21-152	0.35
Enugu	14.97	1-56	115.16	16-362	0.13
Nsukka[18]	14.00	1-40	116.81	21-301	0.12
Orlu	16.19	1-40	51.60	10-120	0.31
Owerri[18]	44	1-120	157.81	75-323	0.28
Port-Harcourt[17, 38]	35.65	8-68	128		0.26
Eket[38]	12.10	1-26	37.90	26-293	0.32
Uyo[38]	29.90	1-110	90.30	5-88	0.33
Calabar[38]	9.70	1-28	39.40	12-385	0.25
Ogoja[38]	8.70	1-20	24.70	4-100	0.35
Ile-Ife[2, 21, 27]	148.19	1.22-986.5	308.61	2-60	0.48
Ewekoro[26]	247.79	9.33-112.14	721.26	0.38-3250	0.34
Lagos[11,13, 14, 17, 21, 29, 30]	56.50	5-462	430.52	41.61-326.75	0.13
Abuja[7, 17]	21.50	7-86	56.50	18-8765	0.38
Kano[17]	63	41-85	340	22-343	0.19
Maiduguri[17]	17	10-23	246	61-757	0.07
WHO 24-hr guideline[63]	25		50	37-370	0.50-0.80
NAAQS 24-hr guideline[51]	35		150		
Athens, Greece[64]	40.20		75.50		0.53
Ashkelon Urb, Israel[65]	24.00		67.10		0.36
Cairo, Egypt[66]	86.24		184.15		0.47
Erdemli, Turkey[67]	9.70		36.40		0.27
Barcelona, Spain[68]	25.00		39.00		0.64
Bliss, Lebanon[69]	40.95		71.34		0.57
Kenitra, Morocco[70]	50.73		110.42		0.46

Table 1 — Comparing Concentration Levels of Particulate Matter in Selected Nigerian Cities and Other Global Cities

implications was conducted by Efe (2008).[19] Results from the study indicated that the urban corridors of over 70% of Nigerian cities are sites with a high rate of daily mean/annual mean ambient PM_{10} of over 120 µg/m^3, while < 30% of Nigerian urban centres had a mean annual ambient PM_{10} value of 119.2 µg/m^3. Similarly, it was noted that significant differences existed in PM_{10} concentrations across different land-use types, between the built-up areas and those of the surrounding rural areas. Findings from the study also revealed that high concentrations of PM_{10} in most Nigerian urban environments have resulted in a significant prevalence of cough, catarrh, eye infection, asthma, chronic bronchitis, etc.[19]

Other fragmented studies of particulate matter levels in different parts of Nigeria have also been reported in areas such as Ile-Ife, Kano, Ibadan, Sapele and Obaretin, Isoko, Ewekoro, and the Ife-Ibadan highway.[20-27]

Multi-elemental characterization of aerosol samples in Nigeria have been carried out using an array of analytical procedures such as X-ray fluorescence, total reflection X-ray fluorescence, energy dispersive X-ray fluorescence (EDXRF), polarized EDXRF, wave-dispersive X-ray fluorescence, atomic absorption spectroscopy, inductively coupled plasma mass spectrometry, inductively coupled plasma optical emission spectroscopy, instrumental neutron activation analysis (INAA), proton-induced X-ray fluorescence and proton-induced gamma ray emission.[2,7,10-15,17,20-24,27-30]

There have been notable ambient air pollution-related studies in Nigeria during the past three decades. The focus of the present study is on particulate matter ($PM_{2.5}$, PM_{10}) and elemental composition of atmospheric micro-environments investigated in selected geo-political zones of the country, with special emphasis placed on the comparison of sampling techniques, sampling instruments and ambient air pollutant concentrations recorded in the selected studies. Furthermore, an attempt will be made to compare particulate matter and multi-element concentration levels in aerosols of Nigerian environments with similar studies on aerosols of selected cities around the world. Furthermore, relevant standards such as the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA)'s National Ambient Air Quality Standard (NAAQS) guideline limits for $PM_{2.5}$ and PM_{10} in ambient air will be used for comparing data from air pollution studies in Nigeria for the period under review.

Methods

This paper presents an update on ambient air monitoring studies in Nigeria over the last 30 years focusing mainly on the levels of suspended particulate matter ($PM_{2.5}$, PM_{10}) and multi-elements present in Nigerian aerosols as measured in selected diverse receptor sites. The review was conducted by systematically searching the databases of ResearchGate, Google Scholar, MEDLINE, PubMed Central, EBSCOhost and PubMed libraries for original research using search terms such as 'particulate matter loads in Nigeria', '$PM_{2.5}$ and PM_{10} levels in Nigeria', elemental composition of Nigerian aerosols', 'health implications of airborne pollution', 'seasonal variation of particulate matter in Nigerian Cities', 'urban and rural particulate matter loads in Nigeria', 'receptor modelling' and 'source apportionment of airborne particles in Nigeria'. Atmospheric pollutants such as fine suspended particulate matter and trace elements have health implications, especially if they exceed regulatory guidelines. Search results were collated and studied, while systematically extracting results relevant to the review. Searches were not limited to time or place of research, but limited to publications available (originally or translated) in the English language from 1985 to 2015, as shown in Table 1 and Supplemental Materials I–III.

A total of 476 articles were found in the available published literature. On the basis of their title, abstract, key words and full text (when available), the selected publications were further trimmed down to remove papers that did not conform to the above search criteria. Information on $PM_{2.5}$ and PM_{10} levels, $PM_{2.5}$/PM_{10} ratios and elemental concentrations of $PM_{2.5}$ and/or PM_{10} size fraction were then extracted from each relevant published report. Other descriptive information about each study such as geographical location, type of sampler, flow rate, number of samples, analytical methodology, number of elements detected and major pollution sources were also recorded.

Research papers without the above mentioned descriptive information were excluded from the list. If more than one study was available for the same geographical location, particulate matter concentration ranges in the selected different studies were then summed up to get the average particulate matter concentration for that location. Relevant research papers were grouped into classes as follows: 70 articles on aerosol based research, 27 articles on $PM_{2.5}$ and/or PM_{10} levels, 20 articles on source apportionment of air-borne particles and 7 articles on seasonal variation of particulate matter.[1-70]

From the resulting group classes above, further subgroup classes were also created as follows: 5 inter-state monitoring studies, 14 intra-state monitoring studies, 9 studies involving traffic locations, 11 studies involving industrial locations, 3 studies involving educational locations, 9 studies involving commercial locations and 10 studies involving residential locations.[2,7,11-15,17,18,21,22,24, 26-30,33,38,52]

Results

Survey of Air Pollution-Related Research in the 6 Geo-Political Zones and the Federal Capital Territory

South West Zone

Six states (Lagos, Ogun, Osun, Ekiti, Ondo and Oyo) make up the South West zone of Nigeria. The estimated combined population in this zone is 27.7 million.[32] The latest demographic surveys put the population of Lagos between 10-15 million people.[14]

This zone is highly industrialized with major industries located in Lagos, Ogun and Oyo States. Notable locations where air pollution studies have been carried out include Ikoyi, Mushin, Ikeja, Victoria Island, Oba-Akran road, the Mile 2 and Bariga areas of Lagos, Ibadan, Oyo, Ile-Ife, Osun and Ewekoro, Ogun.[11-15,17,20,22,23,26,27,29,30]

Average $PM_{2.5}$ and PM_{10} concentrations in this zone exceeded the WHO and NAAQS 24-hr guideline criteria for $PM_{2.5}$ and PM_{10} except for Mushin (10.8 μg/m^3, 57 μg/m^3), Ikoyi (5.6 μg/m^3, 45.4 μg/m^3), Ikeja (10.2 μg/m^3, 56.4 μg/m^3), Mile 2 (30.88 μg/m^3, 48.27 μg/m^3), Victoria Island (25.27 μg/m^3, 26.11 μg/m^3), Oba-Akran Road (25.55 μg/m^3, 28.18 μg/m^3) and Ile-Ife (25.37 μg/m^3, 37.15 μg/m^3). In addition, except for the previously cited locations with low particulate matter loads comparable to Erdemli, Turkey (9.7 μg/m^3, 36.40 μg/m^3), all other locations in the South West recorded comparably high particulate matter loads when compared to other locations around the world (*Table 1*). According to Efe (2008), observed PM_{10} levels in Ibadan and Lagos were 119.7 μg/m^3 and 122.3 μg/m^3, respectively; which although exceeding the WHO 24-hr limit for PM_{10}, still falls within the corresponding NAAQS daily limit.[19]

South South Zone

Delta, Edo, Cross-River, Akwa-Ibom, Rivers and Bayelsa States are found in the South South zone, otherwise referred to as the Niger Delta, as a result of the abundance of oil and gas reserves in the area. It covers an area of approximately 75,000 km^2, representing 7.5% of Nigeria's total land area. The delta is a vast floodplain built up by the accumulation of sedimentary deposits washed down from the Niger and Benue rivers.[31] According to the 2006 population census figures, approximately 21 million people live in the South South zone.[32] Segregated air pollution studies have been carried out in Port-Harcourt, Rivers State, Sapele in Delta State, Obaretin and Isoko in Edo State.[17,24,25,33] All selected locations in the South South zone exceeded the WHO and NAAQS guideline criteria values for $PM_{2.5}$ and PM_{10}. Furthermore, PM_{10} levels in Warri (122.2 μg/m^3), Benin (119.2 μg/m^3) and Port-Harcourt (118.3 μg/m^3) were higher than the WHO 24-hr guideline of 50 μg/m^3, but lower than the corresponding NAAQS stipulated daily limit of 150 μg/m^3.[19] This trend is a result of gas flaring and other industrial emission activities prevalent in the Niger Delta region. When compared to other locations around the world, particulate matter loads in South South locations ranked comparably high.

South East Zone

The states of Abia, Imo, Anambra, Enugu and Ebonyi are found in the south-eastern part of the country. According to latest population census figures, an estimated 16.4 million people are living in the South East zone.[32] An array of economic, industrial and academic activities take place in this zone. In south-eastern Nigeria, there have been recent attempts to routinely monitor atmospheric particulate matter loads in selected urban areas within the zone. For instance, air quality in Aba, Abia State has been routinely monitored as part of six Nigerian megacities investigated for air pollution data indices. The results indicated comparatively high $PM_{2.5}$ (102 μg/m^3) and PM_{10} (553 μg/m^3) concentrations which were well above the 24-hr air quality guideline limits set by the WHO and NAAQS.[17] Furthermore, 10 selected urban areas (2 from each of the 5 states in the South East zone) in this zone have been routinely monitored for their spatial and seasonal variations over 2 major seasons. Seasonal $PM_{2.5}$ mean concentration ranged from 21.69 ± 9.93 to 122.88 ± 33.90 μg/m^3 (dry season) and 3.31 ± 2.36 to 11.44 ± 4.57 μg/m^3 (wet season), while seasonal PM_{10} mean concentration varied in the range of 55.81 ± 17.09 to 921.34 ± 532.60 μg/m^{3}and 14.38 ± 3.01 to 266.06 ± 129.79 μg/m^3 for the dry and wet seasons, respectively.[18]

In a related study, a PM_{10} level of 121.8 μg/m^3 was recorded in Enugu as part of a mega-city particulate matter monitoring campaign covering 17 cities in Nigeria over a 6-year period.[19] These recorded values showed marked variations when compared with the WHO and NAAQS daily air quality guideline criteria.

Federal Capital Territory

Abuja, which is the Federal Capital Territory of Nigeria, is the most notable city in the North Central zone. According to the 2006 census, Abuja had a population of 1.4 million.[32] Unofficial records put the population at between two million to well over three million. This is unsurprising owing to the huge influx of people into the Federal Capital Territory leading to the emergence of satellite towns such as Karu, Suleja, Gwagwalada, Lugbe, Kuje and other smaller settlements.[7] Notable studies involving routine monitoring and elemental characterisation of atmospheric particulate matter within the greater Abuja Metropolis have been carried out in the recent past.[6,17]

While one study recorded average $PM_{2.5}$ (14 µg/m^3) and PM_{10} (38 µg/m^3) concentrations lower than the WHO and NAAQS 24-hr air quality guidelines for $PM_{2.5}$ and PM_{10} respectively, another study recorded an average $PM_{2.5}$ concentration (29 µg/m^3) higher than the WHO (25 µg/m^3) 24-hr air quality guideline, but within the NAAQS (35 µg/m^3) daily limit, while also recording an average PM_{10} concentration (75 µg/m^3) higher than the WHO (50 µg/m^3) 24-hr air quality guideline, but within the NAAQS (150 µg/m^3) daily limit.[7,17]

North Central Zone

States found in this zone include Plateau, Niger, Kogi, Nassarawa, Kwara and Benue States. The combined population figure for this zone is 18.9 million people.[32] Inhabitants of this zone are mainly engaged in agriculture, cattle rearing and petty trading. Particulate matter (PM_{10}) loads in selected areas of the North Central zone such as Abuja (119 µg/m^3), Lokoja (119.7 µg/m^3), Ilorin (124.3 µg/m^3), Minna (123.9 µg/m^3) and Jos (123.9 µg/m^3) have been found to be within the NAAQS daily limit for PM_{10}, but above the WHO 24-hr limit for PM_{10} in ambient air.[19]

North West Zone

States notable for their industrial (Kano, Kaduna), agricultural and nomadic cattle rearing (Sokoto, Kebbi, Zamfara, Katstina and Jigawa) activities are found in this zone. National population census figures for this zone estimate the population to be 35.9 million people, with Kano ranked as the most populated state in the country with 9.4 million inhabitants.[32] Air monitoring studies in Kano have recorded $PM_{2.5}$ (63 µg/m^3) and PM_{10} (340 µg/m^3) levels noticeably higher than the WHO and NAAQS daily guideline values.[17,20]

In another study, PM_{10} levels in Kano (128.1 µg/m^3), Sokoto (130.1 µg/m^3) and Kaduna (125.3 µg/m^3) were above the WHO 24-hr guideline value for PM_{10}, but lower than the NAAQS daily limit for PM_{10}. These values also ranked high when compared to particulate matter loads from other cities around the world.[19]

North East Zone

Adamawa, Bauchi, Borno, Gombe, Taraba and Yobe States are found in the North East zone of Nigeria. Agriculture, cattle rearing and trading are the major occupations of inhabitants of this zone. The latest population census figures for the North East zone indicate a population of 18.9 million people.[32] Ambient air was monitored in Maiduguri, Borno State as part of a national screening exercise on particulate matter loads in Nigeria carried out between September and October, 2009.[17] Results showed that whereas the average $PM_{2.5}$ (17 µg/m^3) concentration was lower than the corresponding WHO and NAAQS 24-hr guideline values, the average PM_{10} concentration (246 µg/m^3) was exceedingly greater than corresponding WHO and NAAQS 24-hr guideline values for PM_{10} in ambient air.[17] Similarly, high PM_{10} values have been recorded in the North Eastern cities of Maiduguri (132 µg/m^3), Yola (123.9 µg/m^3) and Bauchi (128.3 µg/m^3), which although greater than the WHO daily limit for PM_{10}, were less than the NAAQS 24-hr guideline criteria for PM_{10}.[19]

Discussion

Variations in Nigerian Particulate Matter Micro-Environments: Effects of Location and Climate

Variations in PM_{10} and $PM_{2.5}$ concentrations within different geo-political zones can be attributed to regional changes in meteorological factors (temperature, relative humidity, wind speed and visibility) prevalent in such zones.[34] Nigeria has two major seasons (wet and dry seasons) and selected studies in the past have investigated the spatial and seasonal variation of aerosol loadings with climatic parameters. For instance, seasonal variation of meteorological data with aerosol mass concentration has been investigated in the South West and South South zones.[2,35] In a related study, meteorological data depicting seasonal variation in horizontal visibility of four climatic zones (Sahel, North Central, Southern and Coastal zones) in Nigeria was analyzed over a 30 year period (1984-2013) and the results generally showed that good visibility was obtained in the wet season due to the influence of moisture-laden south-easterly wind blowing in from the Atlantic Ocean resulting in rainfall that impinges on air-borne particulates leading to reduced aerosol loadings.[34] On the other hand, poor visibility was a result of dust-laden north-easterly trade wind blowing in from the Sahara Desert, which transports large quantities of dust and anthropogenic emissions, resulting in increased aerosol loadings.[34]

A common trend in these studies reveals a weak correlation between climatic parameters and particulate matter concentrations, indicating that subject to seasonal variation, air temperatures tend to be directly proportional to aerosol loadings, while precipitation, relative humidity and wind speeds tend to have the opposite effect on aerosol loadings. In general, the northern geo-political zones tend to have higher aerosol loads than the southern zones due to factors such as higher temperatures, higher wind speeds, lower humidity/precipitation and reduced visibility, especially during atmospheric hazes. On the other hand, cities in the southern zones experience shorter dry season periods (October-February) and longer wet seasons (March-September) due to comparatively lower temperatures, lower wind speeds and higher relative humidity/precipitation

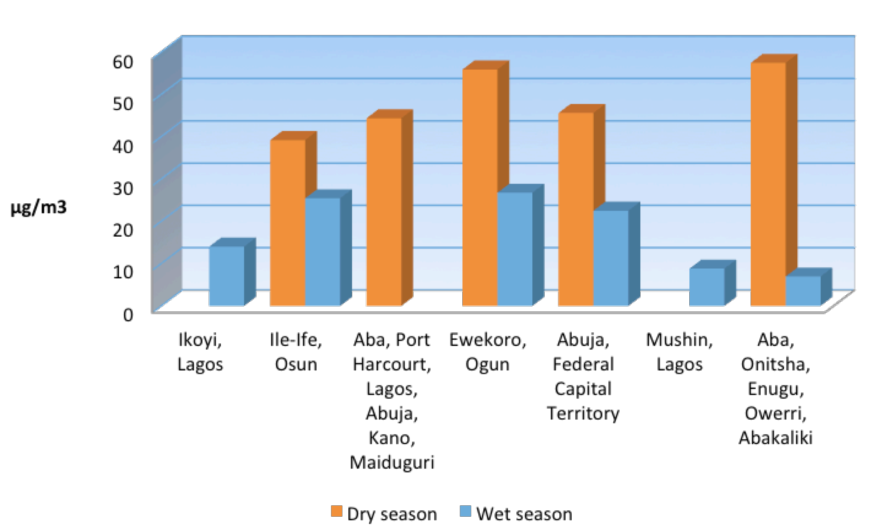

Figure 1 — Seasonal variation of $PM_{2.5}$ in selected cities

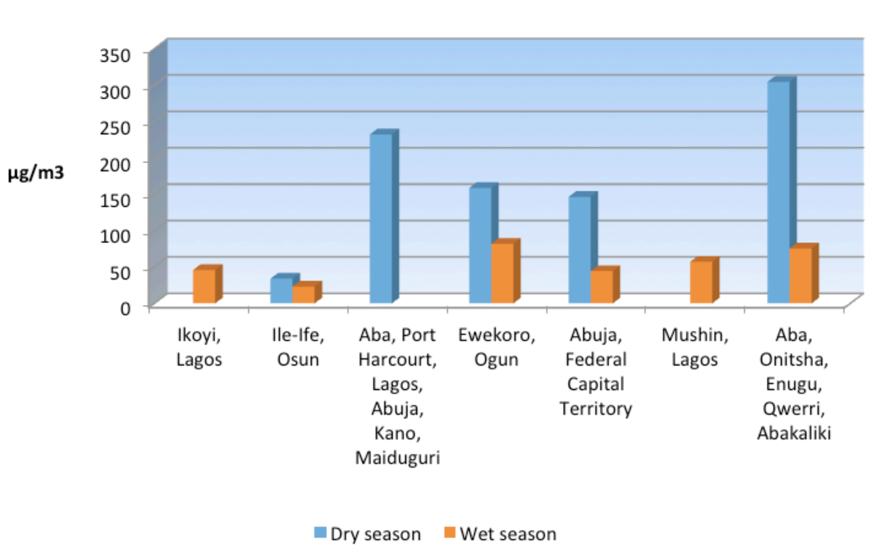

Figure 2 — Seasonal variation of PM_{10} in selected cities.

as opposed to longer dry seasons (November-May) and shorter wet season periods (June-September) in the northern zones.[34,36,37]

In selected locations in the South West (Ile-Ife) and South South (Port-Harcourt) zones, studies have shown an emerging trend depicting weak correlation between meteorological parameters and particulate matter concentrations. In particular, while increasing temperatures lead to increased aerosol loadings and hence increased particulate concentrations, increasing precipitation, relative humidity and wind speeds tend to lower levels of aerosol loadings.[2,35] Relevant studies on cities in Nigeria showing this seasonal trend in particulate matter loads for $PM_{2.5}$ and PM_{10} are depicted in Figures 1 and 2.

Globally, recent studies have revealed that aerosol particles, particularly black carbon and dust, interact strongly with solar and terrestrial radiation by changing atmospheric conditions such as temperature, stability and surface fluxes, which influences cloud development through the modification of their microphysical properties.[71,72] In addition, aerosols can serve as water vapor accumulation sites during cloud droplet formation by functioning as cloud condensation nuclei. In addition, absorption of solar radiation by aerosol particles may contribute to a reduction in cloudiness.[73] Recent studies investigating relationships between aerosols and cloud parameters have shown that cloud cover tends to increase or decrease, depending on aerosol loading.[74-79]

Urban Versus Rural Particulate Matter Loads in Nigerian Cities

There have been few studies comparing particulate matter measurements in urban and rural settings in the published literature in Nigeria.[34] Notable studies in this area include a six year (2001-2006) study of ambient particulate pollution (PM_{10}) in the urban corridors of 17 Nigerian cities and their respective surrounding rural areas.[19] Results obtained from the study showed that PM_{10} concentrations in the rural areas were generally lower than in urban areas. This trend was also observed in a related study of particulate matter loads in selected locations in an urban center and rural area in the Niger Delta region.[33]

Seasonal Variation of Particulate Matter Loads in Nigeria

Seasonal variation of particulate matter loads in Nigeria has been investigated in selected locations in all geo-political zones. For instance, in the South East zone, seasonal monitoring of particulate matter in 10 selected urban centres (Onitsha, Aba, Umuahia, Owerri, Enugu, Nsukka, Abakaliki, Afikpo, Orlu and Nnewi) showed $PM_{2.5}$ concentrations ranging from 14 μg/m^3 in Nsukka town to 66 μg/m^3 in Onitsha, while PM_{10} ranged from 52 μg/m^3 in Orlu to 303 μg/m^3 in Aba.[18,21]

For the South South zone, segregated studies involving the city of Port-Harcourt and 4 other urban centers in the Niger Delta revealed $PM_{2.5}$ concentrations ranging from 20-68 μg/m^3 (Port-Harcourt) and 2-55 μg/m^3 (Eket, Uyo, Calabar, Ogoja and Port-Harcourt).[17,38]

In the South West zone, studies have shown $PM_{2.5}$ levels ranging from 57 μg/m^3 in Lagos to 248 μg/m^3 in Ewekoro, Ogun State, while PM_{10} levels ranged from 309 μg/m^3 in Ile-Ife to 721 μg/m^3 in Ewekoro, Ogun State. The noticeably high particulate matter level in Ewekoro is due to the location of a cement manufacturing company in the town.[2,11,13,14,21,26,27,29,30]

In the North Central zone, selected studies involving Abuja as a study site recorded $PM_{2.5}$ values ranging from 7-86 μg/m^3 and PM_{10} values ranging from 22-343 μ/m^3.[7,17]

In the North West zone, Kano has been used as a study site and recorded $PM_{2.5}$ and PM_{10} concentrations ranging from 41-85 μg/m^3 and 61-757 μg/m^3, respectively.[17]

For the North East zone, Maiduguri has been studied as a sample location and recorded $PM_{2.5}$ and PM_{10} concentrations ranging from 10-23 μg/m^3 and 37-370 μg/m^3, respectively.[17]

Relevant studies on cities in Nigeria showing this seasonal trend in particulate matter loads for $PM_{2.5}$ and PM_{10} are depicted in Figures 1 and 2.

Elemental Compositions of Particulate Matter Loads in Nigeria: Trends in Analytical Techniques and Spatio-Temporal Characteristics

An array of elements ranging from major and minor elements to trace elements have been detected during the instrumental analysis of aerosol samples from different parts of the country. About 40 major, minor and trace elements have been detected in Nigerian aerosols by various researchers (*Supplemental Materials II and III*).

In 1993, a combination of INAA and X-ray fluorescence techniques were used to characterize about 30 elements detected in airborne particulate matter from both Ile-Ife and Kano cities in Nigeria.[20] Similarly, a combination of EDXRF and INAA was used to detect about 25 elements in particulate matter sampled within the premises of 3 Nigerian cement factories. Trace elements such as arsenic (As), lead (Pb), nickel (Ni), cobalt (Co), zinc (Zn), copper (Cu), and chromium (Cr), as well as sulfur (S), calcium (Ca) and phosphorus (P) were found to be highly enriched within the study sites when compared to the control sites. The deposition rate of Ca (a cement marker element) decreased exponentially with increasing distance from the cement factories.[28] In 2001, Oluyemi and Asubiojo reported 15 elements (silicon (Si), aluminium (Al), titanium (Ti), iron (Fe), vanadium (V), Ca, potassium (K), sodium (Na), chlorine (Cl), manganese (Mn), bromine (Br), magnesium (Mg), S, Pb and Zn) determined by a combination of wave-dispersive x-ray fluorescence and atomic absorption spectroscopy.[10]

Furthermore, about 8 elements (V, Cr, Cu, Zn, selenium (Se), Br, strontium (Sr), and Pb) were identified and quantified in suspended particulate matter samples from air corridors of motorways in Ile-Ife and Lagos, Nigeria using total reflection X-ray fluorescence.[21] In addition, about 18 elements were determined in a receptor site close to an industrial estate in Lagos using a combination of wavelength dispersive X-ray fluorescence and atomic absorption spectroscopy.[35] Similarly, about 14 elements (As, Br, Cu, K, lanthanum (La), Na, antimony (Sb), Sr, Zn, cerium (Ce), Co, Cr, scandium (Sc) and thorium (Th)) were detected in particulate matter loadings from a receptor site within Obafemi Awolowo University, Ile-Ife using INAA. The dominant elements detected were Br, K, Na, Sr and Zn.[2]

In addition, 25 elements (Na, Mg, Al, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Se, Br, rubidium (Rb), Sr, cadmium (Cd), tin (Sn), Sb, cesium (Cs), barium (Ba), Pb, and bismuth (Bi)) were simultaneously detected in aerosol samples collected within the vicinity of an iron and steel smelting industry in Lagos using polarized EDXRF. Enriched elements were Mg, Mn, Fe and Zn.[11] In another related study, EDXRF was used to detect about 28 elements (Na, Mg, Al, Si, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, gallium (Ga), As, Br, Rb, Sr, Cd, Sn, samarium (Sm), Pb, and Bi) in aerosol samples collected within and outside the vicinities of an iron and steel smelting industry located along Ife-Ibadan highway, Nigeria.[27]

Twenty-two elements (Si, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Pb, Br, Sr, zirconium (Zr), silver (Ag), Cd and tantalum (Ta)) were detected in both fine and coarse aerosol fractions from a receptor site in Ikoyi, Lagos, while ten elements (As, Br, Ce, K, La, molybdenum (Mo), Na, Sb, Sm and Zn) were detected in aerosol samples from 4 selected receptor sites within Lagos metropolis using the INAA technique.[30] The most abundant metals were Na and K, while all elements except Br, Mo, and

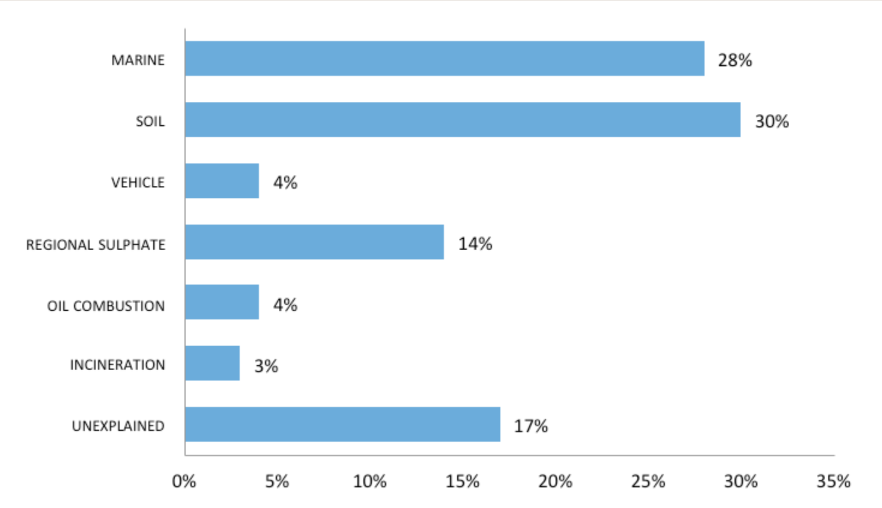

Figure 3a — Source apportionment of $PM_{2.5}$ in Lagos using chemical mass balance and principal component analysis (Oluyemi and Asubiojo, 2001[10])

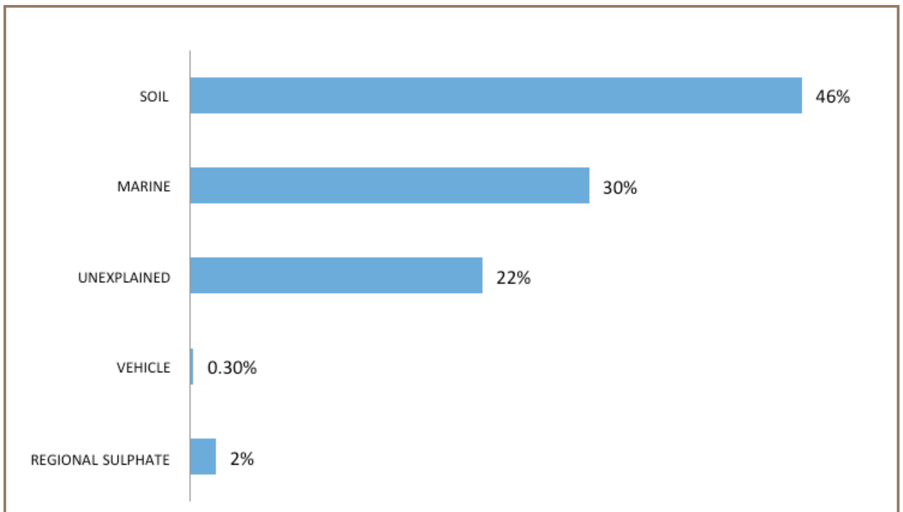

Figure 3b — Source apportionment of $PM_{2.5\text{-}10}$ in Lagos using chemical mass balance and principal component analysis (Oluyemi and Asubiojo, 2001[10])

Sb were predominant in the PM_{10} size fraction.[29]

Furthermore, about 24 elements (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Se, Br, Rb, Sr, Zr, Cs and Pb) were detected in both $PM_{2.5}$ and PM_{10} size fractions from a selected study site in Mushin, Lagos using the proton-induced X-ray emission (PIXE) technique.[13] Similarly, 24 elements were also detected in both fine and coarse fractions of aerosol samples taken from a receptor site in Ikeja, Lagos and analyzed using both PIXE and proton induced gamma ray emission techniques.[14]

Nine elements (Na, Ca, Cr, Mn, Fe, Ni, Cu, Zn and Ba) were detected in coarse-size (PM_{10}) fractions taken from 4 different receptor sites in Ibadan, Nigeria and quantified using the inductively coupled plasma mass spectroscopic technique.[22] Similarly, spatial and temporal variations in suspended particulate matter were measured at 6 different locations within Ibadan and quantified using EDXRF. Major enriched elements with the exception of those with a sea origin were S, Zn, As and Pb.[23]

Eighteen elements (Si, S, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Sn, Ba, Ta and Pb) were detected in $PM_{2.5}$ and PM_{10} fractions from a selected site in Abuja, Nigeria using PIXE analysis. Trace elements were predominantly higher in the PM_{10} fraction than in the $PM_{2.5}$ fraction, and crustal elements such as Si, K and Ca were the most abundant.[7]

Among all the relevant studies surveyed for the period under review, in the $PM_{2.5}$ fraction, Sr recorded the lowest concentration value (0.3±0.3 ng/m^3) in Mushin, Lagos, while Mg recorded the highest concentration value (303.640 ng/m^3) in selected locations within Lagos state.[11,13] For the PM_{10} fraction, Se recorded the least concentration (0.3±0.1 ng/m^3) in Mushin, Lagos, while Sr recorded the highest concentration value

(2, 066, 930±24, 8030 ng/m^3) in Ile-Ife.[2,13]

In addition, for the $PM_{2.5}$ fraction of airborne particulates, a literature survey of related studies revealed that the least detected elements recorded varying mass concentration ranges (ng/m^3) which can be arranged in ascending order as follows: Th (0 - 14±1) < Mo (0 - 27.96 ±4.20) < Ag (0 - 37±60) < Ga (0 - 42±39.33).[2,27,29,30] Similarly, the most detected elements in the $PM_{2.5}$ fraction arranged in ascending order of their mass concentration (ng/m^3) ranges were as follows: Ti (2±8 - 158.67±340.67) < Ni (1±0.1 - 160) < V (2±0.5 - 648 ±0.33) < Cr (2 - 921.67) < Cu (1 - 1,140) < S (72±2 - 1,723.33±1,546.67) < Mn (1±0.3 - 3,880) < Pb (1±0.4 - 3,900±4,033.33) < Si (39±2 - 3,963.33±9,496.67) < Na (24±4 - 9,566±191) < Fe (13 - 38,120) < Zn (3±1) -43,700±47,533.33) < K (55±3 - 61,024±6,100) < Sr (0.3±0.3 - 128,530±15,424).[2,7,11,13,14, 21,27,29,30]

In the case of PM_{10} fraction of airborne particulates, least detected elements arranged in ascending order of increasing mass concentrations (ng/m^3) were: Th (0 - 31±3) < Ga (0 - 35.33±43) < Mo (0 - 35.84±5.38) < Ag (0 - 71±29).[2,27,29,30] Furthermore, the most detected elements in the PM_{10} fraction of airborne particulates exhibited varying mass concentration ranges (ng/m^3) which can be arranged in ascending order as follows: V (6.17±8.27 - 298.33) < Ti (59±5 - 660) < Ni (3±1 - 820) < S (341±5 - 1733.33±1300) < Br (5±0.4 - 2,900) < Cr (2±1 - 3,460) < Cu (3±0.2 - 6,300) < Si (1092±8 - 10, 750.4±17219.2) < K (223±5 - 54, 810±5481) < Mn (8±1 - 59,300) < Pb (5±2 - 67, 060) < Na (683±10 - 73, 871±1477) < Ca (636±25 - 311, 250) < Fe (437±6 - 654, 800) < Zn (24±1 - 730, 280) < Sr (3±0.6 - 2, 066, 930±24, 8030).[2,7,11,13,14,21,22,27]

$PM_{2.5}/PM_{10}$ Ratios in Nigeria

The consideration of $PM_{2.5}/PM_{10}$ ratios in air pollution studies is important as

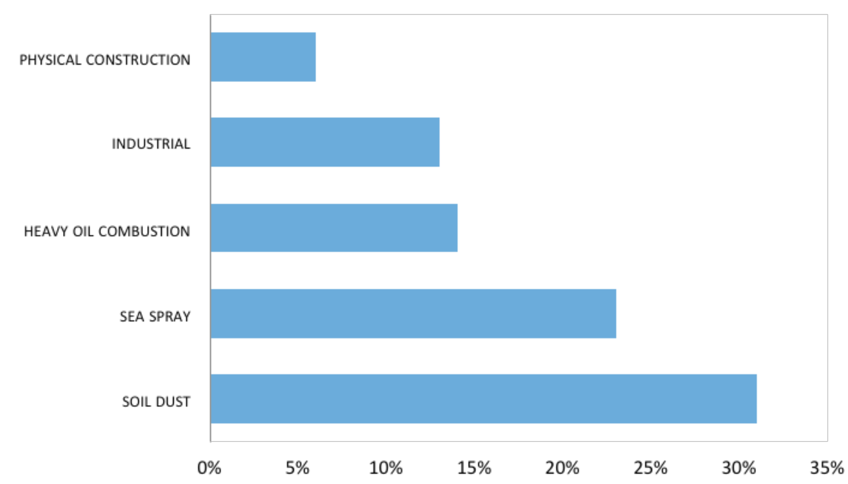

Figure 3c — Source apportionment of $PM_{2.5}$ in Lagos using principal component analysis (Ezeh et al., 2015[14])

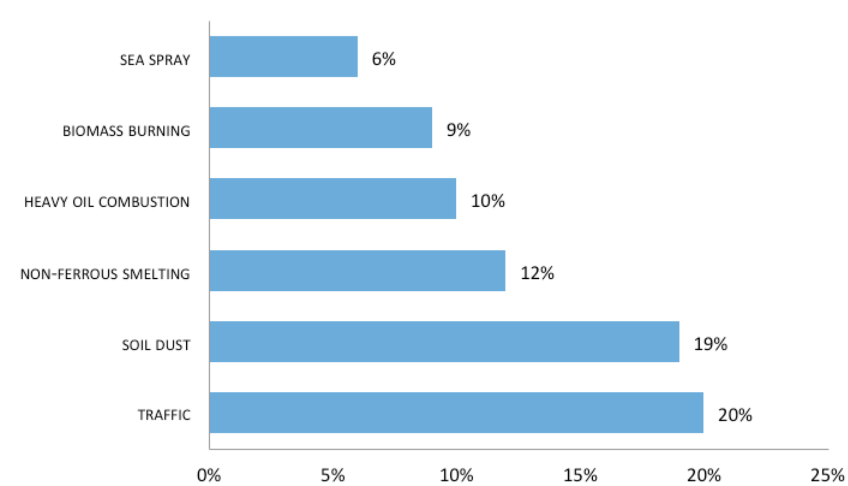

Figure 3d — Source apportionment of $PM_{2.5-10}$ in Lagos using principal component analysis (Ezeh et al., 2015[14])

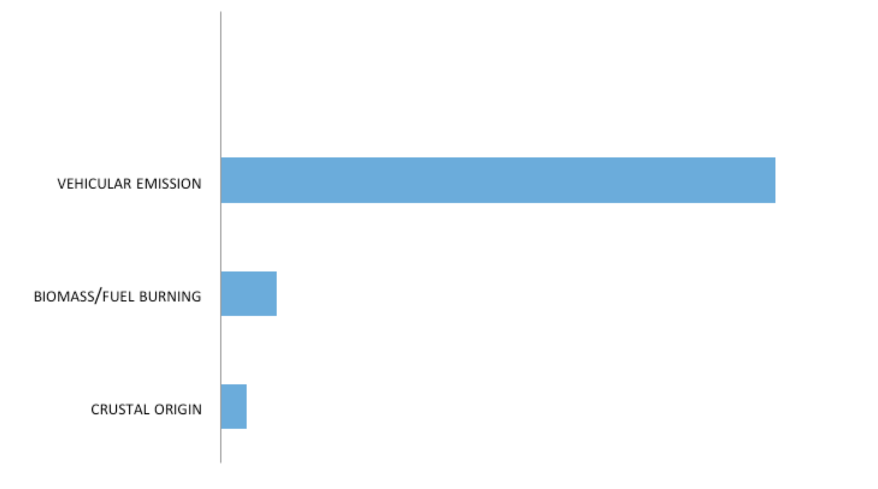

Figure 3e — Source apportionment of $PM_{2.5-10}$ in Abuja using positive matrix factorization (Abiye et al., 2014[16])

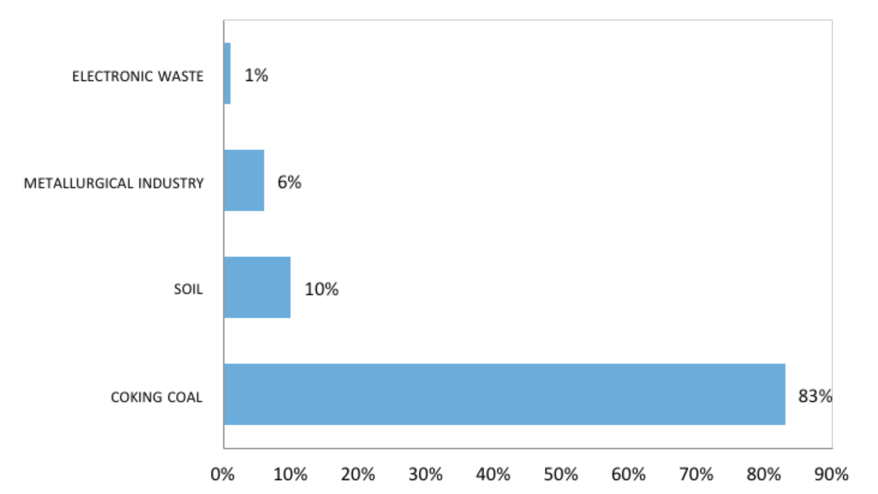

Figure 3f — Source apportionment of $PM_{2.5}$ in Ile-Ife using positive matrix factorization (Owoade et al., 2015[27])

it helps to identify the dominant size fraction in the aerosol samples and the emission sources of the particulate matter. For instance, a high $PM_{2.5}/PM_{10}$ ratio signifies domination by fine particles ($PM_{2.5}$), while a low ratio signifies domination by coarse particles (PM_{10}).[34] Furthermore, high $PM_{2.5}/PM_{10}$ ratios are attributed to particulate air pollution from vehicle emissions and secondary particles formed in the atmosphere from gases. On the other hand, lower ratios are related to strong dust emissions and resuspension due to high traffic volume. Several factors can lead to changes in $PM_{2.5}/PM_{10}$ ratios and these include vehicular emission, high temperature processes, photochemical reactions and a low rate of soil dust resuspension.[36,37]

Available $PM_{2.5}/PM_{10}$ ratios in published air pollution-related studies in Nigeria (*Table 1*) ranged from 0.05 to 0.68, with most of the most of the ratios falling below the 0.5 mark, implying that particulate matter in Nigeria is dominated by coarse particles (PM_{10}).[2,12] Comparatively low % $PM_{2.5}/PM_{10}$ ratios in selected cities in northern Nigeria such as Maiduguri (7%), Kano (19%), Abuja (37%) suggest that the dominant size fraction (PM_{10}) may have as its major contributor the wind-blown dust coming from the Sahara Desert, whereas relatively higher % $PM_{2.5}/PM_{10}$ ratios in selected cities in southern Nigeria such as Ile-Ife (68%) and Lagos (66%) suggests that the dominant size fraction ($PM_{2.5}$) may have as its major contributor marine sources such as the Lagos Lagoon and the Atlantic Ocean.[2,17,29]

Source Apportionment Studies in Nigeria

The use of source apportionment statistical tools [inter-elemental correlation, principal component factor analysis (PCFA) and hierarchical cluster analysis] and relevant receptor modelling techniques [chemical mass balance and positive matrix factorization (PMF)] to accurately pinpoint sources of particulate matter loads is often lacking in air pollution related studies carried out in Nigeria. This is a research gap.

Notable studies that are considered pioneer works in the area of source apportionment and receptor modelling of particulate matter pollution in Nigeria include the use of chemical mass balance and principal component analysis to identify contributory sources of coarse ($PM_{2.5-10}$) and fine ($PM_{2.5}$) particulates at a receptor site in Lagos. Thus, according to a previous study, prominent sources identified as contributors to the particulate matter load at the study site were soil (35-54%), marine (26-34%), automobile exhausts (0.3-3.5%), refuse incineration (2-3%), and regional sulphate (2-12%).[10]

Furthermore, PCFA has been used for source identification of particulate matter loads at four selected receptor sites in Lagos where traffic emission, sea salt, biomass burning, coal combustion and industrial emissions were noted as contributory sources.[29] In a related study, PCFA was also used to apportion five [soil dust (31%), sea spray (23%), heavy oil combustion (14%), industrial (13%) and physical construction (6%)] and six [traffic (20%), soil dust (19%), non-ferrous smelting (12%), heavy oil combustion (10%), biomass burning (9%) and sea spray (6%)] contributory sources for particulate matter for $PM_{2.5-10}$ and $PM_{2.5}$ loads in a receptor site at Ikoyi, Lagos.[15]

In addition, PMF receptor modelling software designed by the USEPA (EPA PMF v5.0.5) has been used for source apportionment analysis of fine ($PM_{2.5}$) and coarse ($PM_{2.5-10}$) particulate fractions from a scrap iron and steel smelting industry located along Ife-Ibadan highway, Nigeria.[27]

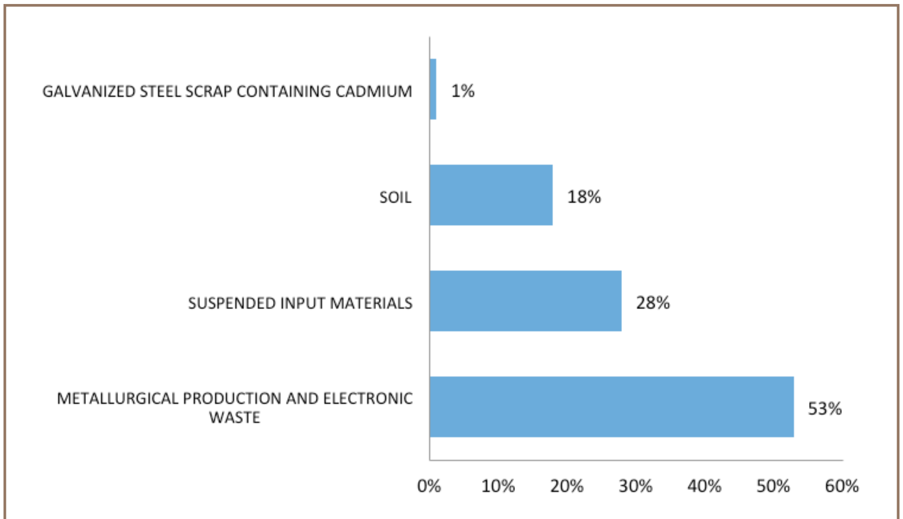

Figure 3g — Source apportionment of $PM_{2.5-10}$ in Ile-Ife using positive matrix factorization (Owoade et al., 2015 [27])

Four source categories were identified for both fine and coarse fractions as follows: $PM_{2.5}$ [coking coal (83%), soil 10%), metallurgical industry (6%) and electronic waste processing (1%)]; $PM_{2.5-10}$ [metallurgical production and electronic waste (53%), suspended input materials (28%), soil (18%) and galvanized steel scrap with cadmium (1%)].[27] Furthermore, another version of the PMF receptor model (EPA PMF v3.0.2.2) was used to assess coarse ($PM_{2.5-10}$) particulate matter source contribution to ambient air in 5 selected locations within Abuja, the Federal Capital Territory of Nigeria.[16] Three distinct sources were identified and apportioned by the PMF model as follows: crustal (4.2%), biomass/fuel burning (8.8%), and vehicular (87%).

Global Trends in Utilization of Tracer Elements for Source Apportionment: the Nigerian Perspective

Apart from elements, organic tracers, inorganic water soluble ions and organic OC/EC content are gaining more recognition as applicable tracers for the source apportionment of carbonaceous aerosols. For instance, in European countries such as Germany, France, Sweden and Norway, anhydrous sugars (levoglucosan, mannosan, galactosan) and radiocarbon isotopes (radiocarbon (^{14}C) and carbon-13 (^{13}C)) have been applied as organic tracers for biomass burning and fossil fuel emission in addition to other source emissions.[39-45]

In addition, water soluble ions such as sulfate (SO_4^{2-}) and nitrate (NO_3) have been utilized as tracers to apportion stationary and mobile source emissions, respectively, in 3 selected Middle Eastern countries. In the same study, organic carbon (OC)/elemental carbon (EC) was also used as a tracer to estimate secondary OC sources in Palestine, Jordan and Israel.[46]

Furthermore, source apportionment of data generated from the United States Supersites Program has revealed that several inorganic marker species can be used to identify major $PM_{2.5}$ sources.[48] Elements such as Al, Si, K, Ca, Fe were used as tracers for road

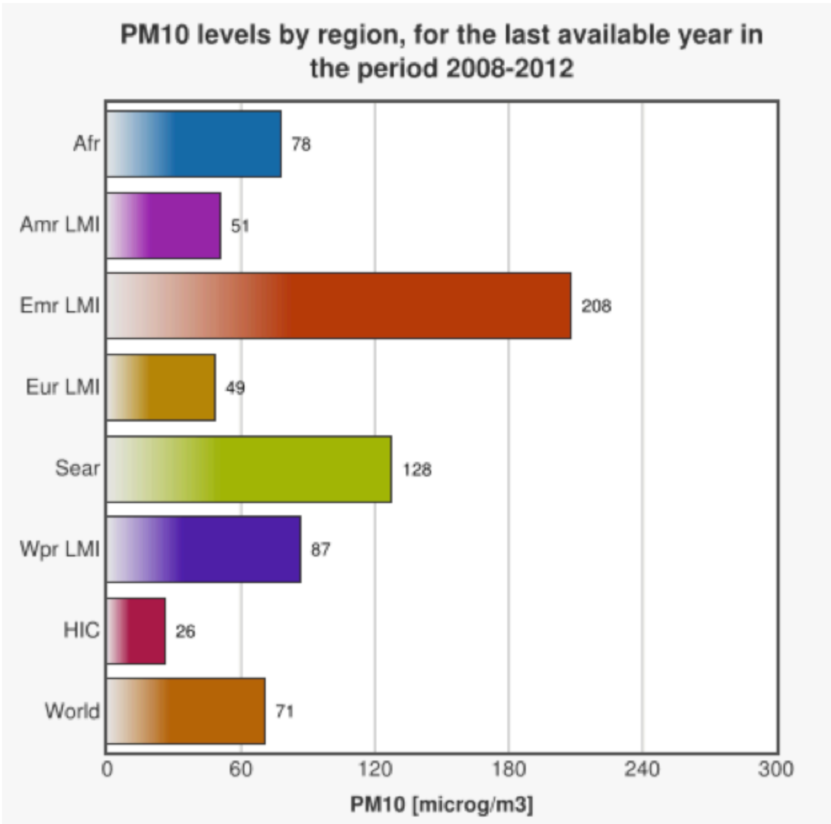

Figure 4 — PM_{10} levels by region, for the last available year in the period 2008-2012. World Health Organization, 2014[80]

Abbreviations: Afr, Africa; Amr, America; Emr, Eastern Mediterranean; Eur, Europe; Sear, Southeast Asia; Wpr, Western Pacific; LMI, Low- and middle-income; HIC, high-income countries. PM_{10} values are regional urban population-weighted.

dust, fugitive windblown dust and dust from construction/demolition activities. Other anthropogenic activities and their applicable tracer markers were farming operations [OC, ammonia (NH_3), ammonium (NH_{4+})], mobile emissions (OC, EC, NH_3, S, Fe, Zn), cooking (OC, EC), fires (OC, EC, K+, Cl-), waste burning and disposal (OC, EC, K+, As, Pb, Zn), industrial fuel combustion (SO_4^{2-}, Se, V, Ni, OC, EC), residential fuel combustion (OC, EC, K+, Cl-), industrial processing (Zn, Pb, Cu, Mn, As, mercury (Hg)), sea salt emissions (Na+, Cl-), secondary aerosol (NO_{3-}, SO_4^{2-}, NH_{4+}) and secondary organic aerosol (OC) formation.[47,48]

In Nigeria, the use of tracer elements to identify source contributors to particulate matter loads is uncommon. Only a handful of notable studies have been able to apply tracers in their particulate matter source apportionment. For instance, similar trace elements have been used in identifying soil and marine sources as contributors to particulate matter loads.[10,49] Another study applied principal component analysis in apportioning source contributors to trace elements found in both fine and coarse fractions depending on the factor loadings of the elements when apportioned to identified factors.[29]

More details about the source contributions to particulate matter loads in selected cities in Nigeria are given in Figures 3(a) to 3(g).

Appraisal of Air Quality Data from Other Regions Around the Globe

According to the latest WHO version of the ambient air pollution database made up of mainly urban air quality data (annual means for PM_{10} and/or $PM_{2.5}$) for about 1600 cities from 91 countries for the years 2008-2013; the global annual PM_{10} concentration is about 71 µg/m^3, while the corresponding values for the 6 WHO classified regions are as follows: Africa: 78 µg/m^3, America: 51 µg/m^3, Eastern Mediterranean: 208 µg/m^3, Europe: 49 µg/m^3, South-East Asia: 128 µg/m^3 and the Western Pacific: 87 µg/m^3 (*Figure 4*).[80]

Based on the findings of the WHO study cited earlier, the great majority of cities worldwide exceed the recommended WHO's Air Quality Guideline for maximum annual PM_{10} mean levels (20 µg/m^3). Globally, relatively few of the monitored cities currently meet the WHO guideline values. These tend to be clustered in high-income countries. Typical concentration ranges for annual PM_{10} mean values of selected cities in each of the 6 WHO classified regions are depicted in Figure 5.

In addition, based on the monitored cities, air quality is poorest in the Eastern Mediterranean and Southeast Asian regions, followed by Latin American and African countries. Based on extrapolations of these data, about half of the urban population live in cities that exceed by 2.5 times or more the recommended levels of fine particulate matter set out by the WHO air quality

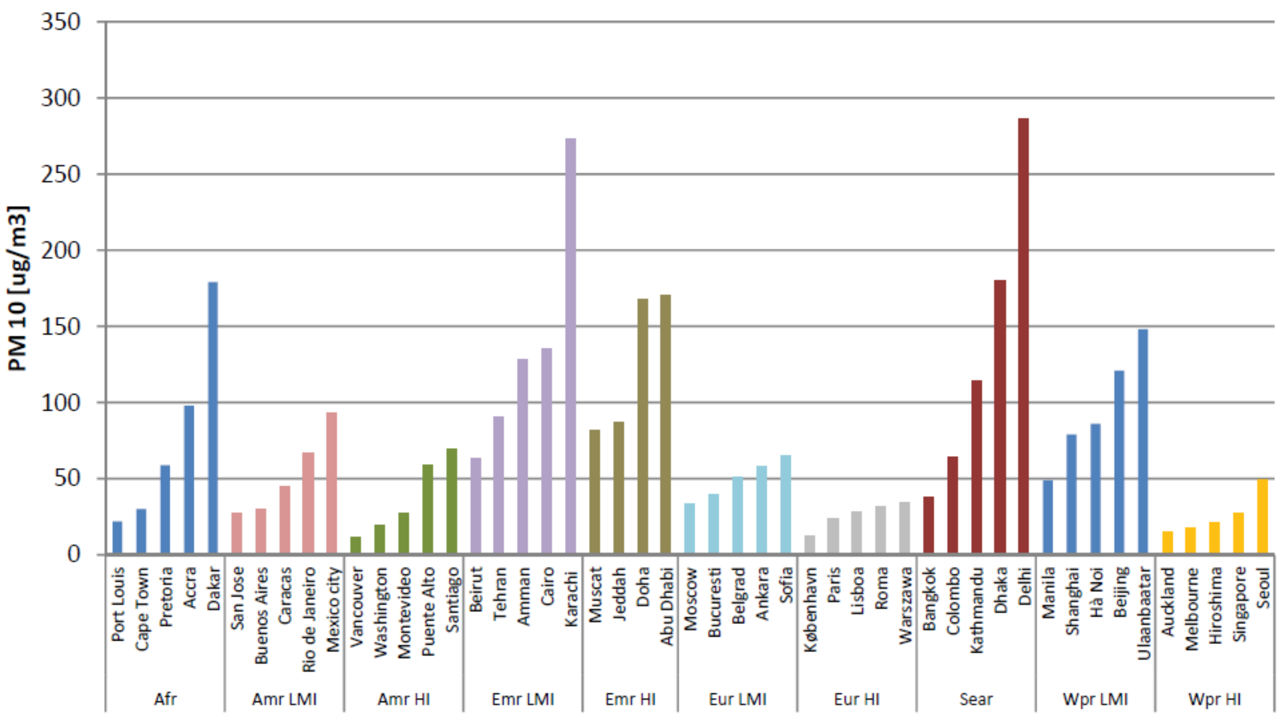

Figure 5 — PM_{10} levels for selected cities by region, for the last available year in the period 2008-2012. World Health Organization, 2014 [80]

Abbreviations: Afr, Africa; Amr, America; Emr, Eastern Mediterranean; Eur, Europe; Sear, Southeast Asia; Wpr, Western Pacific; LMI, Low- and middle-income; HI, high-income.

guidelines and only around 12% of the total urban population live in cities where the air quality complies with such levels (*Figure 6*).[80]

Conclusion

This review attempted to portray the recent trends in air pollution-related research in Nigeria over the last three decades (1985-2015). $PM_{2.5}$ concentrations ranged from 5-248 µg/m³, while PM_{10} concentration ranges from 18-926 µg/m³, revealing that about 50% of the particulate matter loads in Nigeria exceeded both the WHO (25 µg/m³, 50 µg/m³) and NAAQS (35 µg/m³, 150 µg/m³) guideline limits for $PM_{2.5}$ and PM_{10}, respectively.

The world's average annual PM_{10} levels by region range from 26 to 208 µg/m³, with a global average of 71 µg/m³, suggesting that particulate matter load levels in Nigeria compare favorably with other low-income emerging economies in Southeast Asia and the Eastern Mediterranean, but perform poorly when compared to high-income economies in Europe, America and the Western Pacific.

Most of the $PM_{2.5}/PM_{10}$ ratios in Nigeria fall below the 0.5 mark, implying that particulate matter in Nigeria is dominated by coarse, rather than fine particles. Average highest concentrations order of metallic elements for $PM_{2.5}$ were Mg > Sr > K > Zn > Fe > Na > Al > Cl > Pb > Si, while those of PM_{10} were Sr > Zn > Fe > Mg > Ca >Na > Pb > Mn > K > Al. Seasonal variation of particulate matter loads reveals higher concentrations during the dry season than during the rainy season. In addition, particulate matter loads in rural areas were generally lower than their corresponding loads in urban areas. Wind-blown dust from the Sahara Desert is the major contributor to particulate matter loads in northern zones of the country, while sea spray and crustal matter are highest contributors to particulate matter loads in southern zones.

Ambient air monitoring in Nigeria remains largely unregulated and uncoordinated despite efforts by local researchers and relevant government agencies such as the National Environmental Standards and Regulatory Agency and the Nigerian

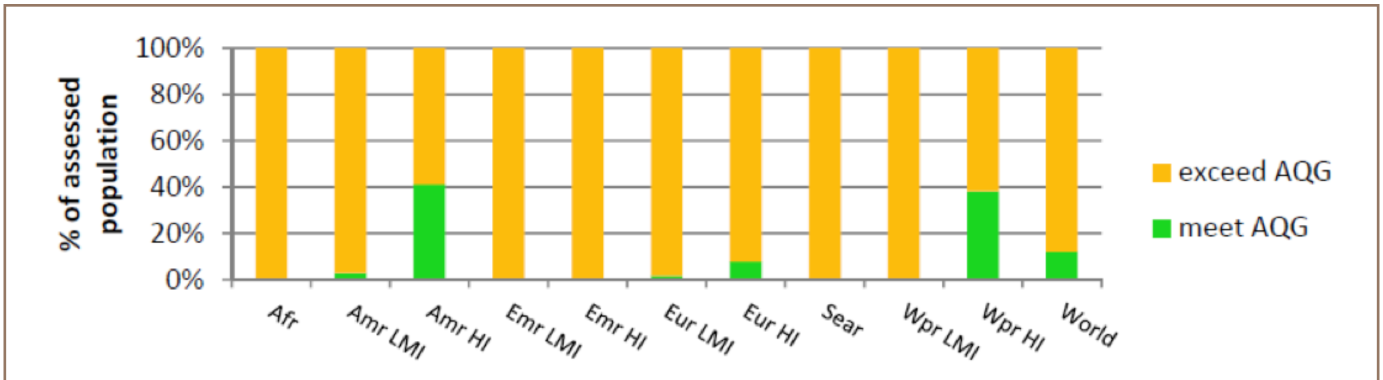

Figure 6 — Annual mean particulate matter for the assessed urban population compared to the WHO air quality guidelines (AQG). World Health Organization, 2014[80]

Abbreviations: Afr, Africa; Amr, America; Emr, Eastern Mediterranean; Eur, Europe; Sear, Southeast Asia; Wpr, Western Pacific; LMI, Low- and middle-income; HI, high-income. Annual mean PM_{10}: 20 µg/m^3; Annual mean $PM_{2.5}$: 10 µg/m^3

Metrological Agency. To remedy this situation, we recommend the development of a national emission standard for suspended particulate matter, establishment of national air quality monitoring networks in major urban/rural areas in the country, fixing emission caps and taxes for industries, road pricing for automobiles during rush hour periods to discourage traffic emissions and stoppage of gas flaring. There is also a need for further research in the area of source apportionment and secondary aerosols to complement current efforts at quantifying particulate matter loads and their elemental concentrations.

References

1. **Pfeiffer RL**. Sampling for PM_{10} and $PM_{2.5}$ particulates In: Hatfield JL, Baker JM, editors. Micrometeorology in agricultural systems: agronomy monograph 47 [Internet]. Madison, WI: American Society of Agronomy; 2005 Jan 1 [cited 2015 Nov 12]. p. 227-45. Paper No.: 1393. Available from: http://digitalcommons.unl.edu/usdaarsfacpub/1393
2. **Owoade OK, Olise FS, Ogundele LT, Fawole OG, Olaniyi HB**. Correlation between particulate matter concentrations and meteorological parameters at a site in Ile-Ife, Nigeria. *Ife J Sci* [Internet]. 2012 [cited 2016 May 12];14(1):83-93. Available from: http://scholar.oauife.edu.ng/ijs/files/owoade.pdf
3. **Obioh IB, Oluwole AF, Akeredolu FA**. Atmospheric lead emissions and source strengths in Nigeria: 1988 Inventory. In: Allan RJ, Nriagu JO, editors. Heavy metals in the environment. Edinburgh, Scotland: CEC Consultants; 1994. p. 271–4.
4. Measurement of suspended particulate matter in ambient air. In: GEMS/AIR Methodology Reviews. Vol. 3. Nairobi, Kenya: United Nations Environment Programme; 1994. Document No.: WHO/EOS/94.3, UNEP/GEMS/94.A.4.
5. Health aspects of air pollution with particulate matter, ozone and nitrogen dioxide [Internet]. Bonn, Germany: World Health Organization; 2003 Jan 13-5 [cited 2015 Nov 12]. 94 p. Report No.: EUR/03/5042688. Available from: http://www.euro.who.int/__data/assets/pdf_file/0005/112199/E79097.pdf
6. **Fantke P, Jolliet O, Evans JS, Apte JS, Cohen AJ, Hanninen OO, Hurley F, Jantunen MK, Jerrett M, Levy JI, Loh MM, Marshall JD, Miller BG, Preiss P, Spadaro JV, Tainio M, Tuomisto JT, Weschle CJ, McKone TE**. Health effects of fine particulate matter in life cycle impact assessment: findings from the Basel Guidance Workshop. *Int J Life Cycle Assess* [Internet]. 2015 Feb [cited 2016 May 12];20(2):276-88. Available from: http://personal.ce.umn.edu/~marshall/Marshall_46.pdf
7. **Abiye OE, Obioh IB, Ezeh GC**. Elemental characterization of urban particulates at receptor locations in Abuja, North-Central, Nigeria. *Atmospheric Environ* [Internet]. 2013 Dec [cited 2016 May 12];81:695–701. Available from: http://www.sciencedirect.com/science/article/pii/S1352231013006626 Subscription required to view.
8. **Laing RK, Obioh IB**. Emission inventory for Nigeria with CAREAIR. *Environ Monit Assess* [Internet]. 1994 May [cited 2016 May 12];31(1-2):115-24. Available from: http://link.springer.com/article/10.1007%2FBF00547186 Subscription required to view.
9. **Oluyemi EA, Asubiojo OI, Oluwole AF, Toussaint CJ.** Elemental concentrations and source identification of air particulate matter at a Nigerian site: a preliminary study. *J Radioanal Nucl Chem* [Internet]. 1994 Apr [cited 2016 May 12];179(2):187-194. Available from: http://link.springer.com/article/10.1007%2FBF02040152 Subscription required to view.
10. **Oluyemi EA, Asubiojo OI.** Ambient air particulate matter in Lagos, Nigeria: a study using receptor modeling with X-ray fluorescence analysis. *Bull Chem Soc Ethiop* [Internet]. 2001 [cited 2016 May 12];15(2):97-108. Available from: http://www.ajol.info/index.php/bcse/article/view/20956/3900
11. **Owoade OK, Olise FS, Obioh IB, Olaniyi HB, Ferrero L, Bolzacchini E.** EDXRF elemental assay of airborne particulates: a case study of an iron and steel smelting industry, Lagos, Nigeria. *Sci Res Essays* [Internet]. 2009 Nov [cited 2016 May 12];4(11):1342-7. Available from: http://www.academicjournals.org/article/article1380627511_Owoade%20et%20al.pdf
12. **Owoade KO, Olise FS, Olaniyi HB, Bolzacchini E.** An ICP-OES, TXRF and EDXRF analysis of airborne particulate samples in an iron and steel smelter environment. *Toxicol Environ Chem* [Internet]. 2009 [cited

2016 May 12];91(5):873-81. Available from: http://www.tandfonline.com/doi/full/10.1080/02772240802614580 Subscription required to view.

13. **Ezeh GC, Obioh IB, Asubiojo OI, Chiari M, Nava S, Calzolai G, Lucarelli F, Nuviadenu CK**. Elemental compositions of PM_{10}-2.5 and $PM_{2.5}$ aerosols of a Nigerian urban city using ion beam analytical techniques. *Nucl Instrum Methods Phys Res*. Section B, Beam Interactions with Materials and Atoms [Internet]. 2014 Sep 1 [cited 2016 May 12];334:28-33. Available from: http://www.sciencedirect.com/science/article/pii/S0168583X14005242 Subscription required to view.

14. **Ezeh GC, Obioh IB, Asubiojo OI, Chiari M, Nava S, Calzolai G, Lucarelli F, Nuviadenu C**. The complementarity of PIXE and PIGE techniques: a case study of size segregated airborne particulates collected from a Nigeria city. *Appl Radiat Isot* [Internet]. 2015 Sep [cited 2016 May 12];103:82-92. Available from: http://www.sciencedirect.com/science/article/pii/S0969804315300348 Subscription required to view.

15. **Ezeh GC, Obioh IB, Asubiojo OI**. Multi-elemental analysis and source apportionment of urban aerosols in a low density residential area: a case study of Ikoyi Lagos Nigeria. *Ife J Sci* [Internet]. 2015 [cited 2016 May 12];17(2):415-27. Available from: http://www.ajol.info/index.php/ijs/article/view/131742/121343

16. **Abiye OE, Obioh IB, Ezeh GC, Alfa A, Ojo EO, Ganiyu AK**. Receptor modeling of atmospheric aerosols in Federal Capital Territory (FCT), Nigeria. *Ife J Sci* [Internet]. 2014 [cited 2016 May 12];16(1):107-19. Available from: http://www.ajol.info/index.php/ijs/article/view/131571/121169

17. **Obioh IB, Ezeh GC, Abiye OE, Alfa A, Ojo EO, Ganiyu AK**. Atmospheric particulate matter in Nigerian megacities. *Toxicol Environ Chem* [Internet]. 2013 Apr 23 [cited 2016 May 12];95(3):379–85. Available from: http://www.tandfonline.com/doi/full/10.1080/02772248.2013.790970 Subscription required to view.

18. **Ngele SO, Kalu FO.** Measurements of ambient air fine and coarse particulate matter in ten South-East Nigerian cities. *Res J Chem Sci* [Internet]. 2015 Jan [cited 2016 May 12];5(1):71-7. Available from: http://www.isca.in/rjcs/Archives/v5/i1/12.ISCA-RJCS-2015-004.pdf

19. **Efe SI**. Spatial distribution of particulate air pollution in Nigerian cities: implications for human health. *J Environ Health Res* [Internet]. 2008 [cited 2016 May 12];7(2). Available from: http://www.cieh.org/jehr/jehr2column.aspx?id=14688

20. **Asubiojo OI, Obioh IB, Oluyemi EA, Oluwole AF, Spyrou NM, Farooqi AS, Arshed W, Akanle OA**. Elemental characterization of airborne particulates at two Nigerian locations during the Harmattan season. *J Radioanal Nucl Chem* [Internet]. 1993 Jan [cited 2016 May 12];167(2):283–93. Available from: http://link.springer.com/article/10.1007%2FBF02037187 Subscription required to view.

21. **Obioh IB, Olise FS, Owoade OK, Olaniyi HB.** Chemical characterization of suspended particulate along air corridors of motorways in two Nigerian cities. *J Appl Sci* [Internet]. 2005 [cited 2016 May 12];5(2):347-50. Available from: http://scialert.net/fulltext/?doi=jas.2005.347.350

22. **Odeshi TA, Ana GR, Sridhar MK, Olatunji AO, Abimbola AF**. Outdoor air particle-bound trace metals in four selected communities in Ibadan, Nigeria. *Environ Geochem Health* [Internet]. 2014 Aug [cited 2016 May 12];36(4):755-64. Available from: http://link.springer.com/article/10.1007%2Fs10653-014-9593-8 Subscription required to view.

23. **Akinlade GO, Olaniyi HB, Olise FS, Owoade OK, Almeida SM, Almeida-Silva M, Hopke PK**. Spatial and temporal variations of the particulate size distribution and chemical composition over Ibadan, Nigeria. *Environ Monit Assess* [Internet]. 2015 Aug [cited 2016 May 12];187(8):544. Available from: http://link.springer.com/article/10.1007%2Fs10661-015-4755-4 Subscription required to view.

24. **Ediagbonya TF, Ukpebor EE, Okieimen FE, Momoh OL, Yusef**. Elemental concentration of inhalable and respirable particulate matter in urban area during wet season. *J Appl Sci Environ Manag* [Internet]. 2014 Mar [cited 2016 May 12];18(1):78-83. Available from: http://www.ajol.info/index.php/jasem/article/view/103930/94046

25. **Aziakpono OM, Ukpebor EE, Ukpebor JE**. Baseline, spatial and temporal variation of respirable ($PM_{2.5}$) particulate matter in Isoko Land. *Greener J Phy Sci* [Internet]. 2013 Nov [cited 2016 May 12];3(7):247-54. Available from: http://www.gjournals.org/GJPS/GJPS%20PDF/2013/November/130913840%20Aziakpono%20et%20al.pdf

26. **Bada BS, Olatunde KA, Oluwajana A**. Air quality assessment in the vicinity of Cement Company. *Int J Nat Sci* [Internet]. 2013 Jun [cited 2016 May 12];1(2):34-42. Available from: http://www.eajournals.org/wp-content/uploads/AIR-QUALITY-ASSESSMENT-IN-THE-VICINITY-OF-CEMENT-COMPANY.pdf

27. **Owoade KO, Hopke PK, Olise FS, Ogundele LT, Fawole OG, Olaniyi BH, Jegede OO, Ayoola MA, Bashiru MI**. Chemical compositions and source identification of particulate matter ($PM_{2.5}$ and $PM_{2.5}$-10) from a scrap iron and steel smelting industry along the Ife-Ibadan highway, Nigeria. *Atmospheric Pollut Res* [Internet]. 2015 Jan [cited 2016 May 12];6(1):107-19. Available from: http://www.sciencedirect.com/science/article/pii/S1309104215302579

28. **Adejumo JA, Obioh IB, Ogunsola OJ, Akeredolu FA, Olaniyi HB, Asubiojo OI, Oluwole AF, Akanle OA, Spyrou NM**. The atmospheric deposition of major, minor and trace elements within and around three cement factories. *J Radioanal Nucl Chem* [Internet]. 1994 Apr [cited 2016 May 12];179(2):195-204. Available from: http://link.springer.com/article/10.1007%2FBF02040153 Subscription required to view.

29. **Owoade OK, Fawole OG, Olise FS, Ogundele LT, Olaniyi HB, Almeida MS, Ho MD, Hopke PK**. Characterization and source identification of airborne particulate loadings at receptor site-classes of Lagos Mega-City, Nigeria. *J Air Waste Manag Assoc* [Internet]. 2013 Sep [cited 2016 May 12];63(9):1026-35. Available from: https://www.researchgate.net/publication/258037601_Characterization_and_source_identification_of_airborne_particulate_loadings_at_receptor_site-classes_of_Lagos_Mega-City_Nigeria

30. **Ezeh GC, Obioh IB, Asubiojo OI, Abiye OE**. PIXE characterization of PM_{10} and $PM_{2.5}$ particulates sizes collected in Ikoyi Lagos, Nigeria. *Toxicol Environ Chem* [Internet]. 2012 [cited 2016 May 12];94(5):884-94. Available from: http://www.tandfonline.com/doi/abs/10.1080/02772248.2012.674133?journalCode=gtec20 Subscription required to view.

31. **Sojinu OS, Wang JZ, Sonibare OO, Zeng EY**. Polycyclic aromatic hydrocarbons in sediments and soils from oil exploration areas of the Niger Delta, Nigeria. *J Hazard Mater* [Internet]. 2010 Feb 15 [cited 2016 May 12];174(1-3):641-7. Available from: http://www.sciencedirect.com/science/article/pii/S030438940901560X Subscription required to view.

32. **Legal notice and publication of details of the breakdown of the national and state provisional totals of 2006 census.** Federal Republic of Nigeria Official Gazette. 2007 May 15;94(24):175-98.

33. **Ediagbonya TF, Ukpebor EE, Okieimen FE, Okungbowa GE**. Comparative study of TSP, inhalable particles and respirable particles in urban and rural areas in Niger Delta region of Nigeria. *Greener J Phy Sci* [Internet]. 2012 Sep [cited 2016 May 12];2(3):89-96. Available from: http://www.gjournals.org/GJPS/GJPS%20PDF/2012/September/Ediagbonya%20et%20al.pdf

34. **Balarabe M, Abdullah K, Nawawi M**. Long-term trend and seasonal variability of horizontal visibility in Nigerian troposphere. *Atmosphere* [Internet]. 2015 Oct 2 [cited 2016 May 12];6(10):1462-86. Available from: http://www.mdpi.com/2073-4433/6/10/1462/htm

35. **Weli VE**. Spatial and seasonal influence of meteorological parameters on the concentration of suspended particulate matter in an industrial city of Port Harcourt, Nigeria. *Dev Ctry Stud* [Internet]. 2014 [cited 2016 May 12];4(10):112-20. Available from: http://www.iiste.org/Journals/index.php/DCS/article/viewFile/12868/13448

36. **Nigeria's first national communication under the United Nations framework convention on climate change** [Internet]. Abuja, Nigeria: The Ministry of Environment of the Federal Republic of Nigeria; 2003 Nov [cited 2016 May 12]. 132 p. Available from: http://unfccc.int/resource/docs/natc/nignc1.pdf

37. **Oyem AA, Igbafe AI**. **Analysis of the atmospheric aerosol loading over Nigeria.** *Environ Res J* [Internet]. 2010 [cited 2016 May 12];4(1):145-56. Available from: http://www.medwelljournals.com/fulltext/?doi=erj.2010.145.156

38. **Ngele SO, Onwu FK**. **Ambient air particulate matter levels in selected urban centres of Niger Delta region, Nigeria.** *Int Res J of Environ Sci* [Internet]. 2015 Apr [cited 2016 May 12];4(4):54-63. Available from: http://www.isca.in/IJENS/Archive/v4/i4/9.ISCA-IRJEvS-2015-029.pdf

39. **Cavalli F, Viana M, Yttri KE, Genberg J, Putaud JP.** **Toward a standardised thermal-optical protocol for measuring atmospheric organic and elemental carbon: the EUSAAR protocol.** *Atmospheric Meas Tech* [Internet]. 2010 Jan 26 [cited 2016 May 12];3(1):79-89. Available from: http://www.atmos-meas-tech.net/3/79/2010/amt-3-79-2010.pdf

40. **Crippa M, Canonaco F, Lanz VA, Aijala M, Allan JD, Carbone S, Capes G, Ceburnis D, Dall'Osto M, Day DA, DeCarlo PF, Di Marco CF, Ehn M, Eriksson A, Freney E, Ruiz LH, Hillamo R, Jimenez JL, Junninen H, Kiendler-Scharr A, Kortelainen1 AM, Kulmala M, Laaksonen A, Mensah AA, Mohr C, Nemitz E, O'Dowd C, Ovadnevaite J, Pandis SN, Petaja T, Poulain L, Saarikoski S, Sellegri K, Swietlicki E, Tiitta P, Worsnop DR, Baltensperger U, Prevot AS.** **Organic aerosol components derived from 25 AMS data sets across Europe using a newly developed ME-2 based source apportionment strategy.** *Atmospheric Chem Phys* [Internet]. 2013 Sep [cited 2016 May 12];13(9):23325-71. Available from: http://www.atmos-chem-phys.net/14/6159/2014/acp-14-6159-2014.pdf

41. **Szidat S, Bench G, Bernardoni V, Calzolai G, Czimczik CI, Derendorp L, Dusek U, Elder K, Fedi M, Genberg J, Gustafsson O, Kirillova E, Kondo M, McNichol AP, Perron N, dos Santos GM, Stenstrom K, Swietlicki E, Uchida M, Vecchi R, Wacker L, Zhang Y, Prevot AS**. **Intercomparison of 14C analysis of carbonaceous aerosols: exercise 2009.** *Radiocarbon* [Internet]. 2013 [cited 2016 May 12];55(3-4):1496-1509. Available from: https://journals.uair.arizona.edu/index.php/radiocarbon/article/view/16314/pdf

42. **Waked A, Favez O, Alleman LY, Piot C, Petit JE, Delaunay T, Verlinden E, Golly B, Besombes JL, Jaffrezo JL, Leoz-Garziandia E**. **Source apportionment of PM_{10} in a north-western Europe regional urban background site (Lens, France) using positive matrix factorization and including primary biogenic emissions.** *Atmospheric Chem Phys* [Internet]. 2014 Apr 3 [cited 2016 May 12];14:3325-46. Available from: http://www.atmos-chem-phys.net/14/3325/2014/acp-14-3325-2014.pdf

43. **Genberg J, Hyder M, Stenstrom K, Bergstrom R, Simpson D, Fors EO, Jonsson JA, Swietlicki E**. **Source apportionment of carbonaceous aerosol in southern Sweden.** *Atmospheric Chem Phys* [Internet]. 2011 Nov 16 [cited 2016 May 12];11:11387-400. Available from: http://www.atmos-chem-phys.net/11/11387/2011/acp-11-11387-2011.pdf

44. **Yttri KE, Simpson D, Stenstrom K, Puxbaum H, Svendby T.** **Source apportionment of the carbonaceous aerosol in Norway - quantitative estimates based on 14C, thermal-optical and organic tracer analysis.** *Atmospheric Chem Phys* [Internet]. 2011 Mar 3 [cited 2016 May 12];11;9375-94. Available from: http://www.atmos-chem-phys.org/11/9375/2011/acp-11-9375-2011.pdf

45. **Yttri KE, Simpson D, Nojgaard JK, Kristensen K, Genberg J, Stenstrom K, Swietlicki E, Hillamo R, Aurela M, Bauer H, Offenberg JH, Jaoui M, Dye C, Eckhardt S, Burkhart JF, Stohl A, Glasius M**. **Source apportionment of the summer time carbonaceous aerosol at Nordic rural background sites.** *Atmospheric Chem Phys* [Internet]. 2011 Jun 6 [cited 2016 May 12];11:13339-57. Available from: http://www.atmos-chem-phys.net/11/13339/2011/acp-11-13339-2011.pdf

46. **Abdeen Z, Qasrawi R, Heo J, Wu B, Shpund J, Vanger A, Sharf G, Moise T, Brenner S, Nassar K, Saleh R, Al-Mahasneh QM, Sarnat JA, Schauer JJ.** **Spatial and temporal variation in fine particulate matter mass and chemical composition: The Middle East consortium for aerosol research study.** *Sci World J* [Internet]. 2014 [cited 2016 May 12];2014:1-16. Available from: http://www.hindawi.com/journals/tswj/2014/878704/

47. Schauer JJ. Analysis of particle-phase organic speciation data to assess sources of particulate matter. Madison, WI: University of Wisconsin; 2005.

48. **Watson JG, Chen LW, Chow JC, Doraiswamy P, Lowenthal DH.** **Source apportionment: findings from the U.S. Supersites Program.** *J Air Waste Manag Assoc* [Internet]. 2008 Feb [cited 2016 May 12];58(2):265-88. Available from: http://www.tandfonline.com/doi/pdf/10.3155/1047-3289.58.2.265

49. **Taiwo AM, Arowolo TA, Abdullahi KL, Taiwo OT**. **Particulate matter pollution in Nigeria: a review** [Internet]. The 14th International Conference on Environmental Science and Technology; 2015 Sep 3-5; Rhodes, Greece. [place unknown]: The International Conference on Environmental Science and Technology; [2015?] [cited 2016 May 12]. 4 p. Available from: http://cest.gnest.org/cest15proceedings/public_html/papers/cest2015_00342_poster_paper.pdf

50. **Oluyemi EA, Asubiojo OI, Oluwole AF, Toussaint CJ.** **Elemental concentrations and source identification of air particulate matter at a Nigerian site: a preliminary study.** *J Radioanal Nucl Chem* [Internet]. 1994 Apr [cited 2016 May 12];179(2):187-94. Available from: http://link.springer.com/article/10.1007%2FBF02040152 Subscription required to view.

51. **Particulate matter: regulatory actions** [Internet]. Washington D.C.: United States Environmental Protection Agency; 2013 [updated 2016 Feb 23; cited 2015 Nov 12]. [about 5 screens]. Available from: http://www.epa.gov/pm/actions.html

52. **Owoade OK, Jegede OO, Ayoola MA, Fawole OG, Bashiru MI, Olise FS, Ogundele LT**. **Concentrations of particulate matter from an iron-smelting plant located along a busy highway in South-Western Nigeria.** *Ife J Sci* [Internet]. 2013 Jun [cited 2016 May 12];15(1):31-9. Available from: https://www.researchgate.net/publication/235983761_Concentrations_of_Particulate_Matter_from_an_Iron-Smelting_Plant_located_along_a_busy_highway_in_Southwestern_Nigeria

53. **Hildermann LM, Markowski GR, Cass GR**. **Chemical composition of emissions from urban sources of fine organic aerosol.** *Environ Sci Technol* [Internet]. 1991 [cited 2016 May 12];25(4):744-59. Available from: http://pubs.acs.org/doi/abs/10.1021/es00016a021 Subscription required to view.

54. **Andreae MO**. **Soot carbon and excess fine potassium: long-range transport of combustion-derived aerosols.** *Sci* [Internet]. 1983 Jun 10 [cited 2016 May 12];220(4602):1148-51. Available from: http://science.sciencemag.org/content/220/4602/1148.long Subscription required to view.

55. **Rojas CM, Van Grieken RE**. **Electron microprobe characterization of individual aerosol particles collected by aircraft above the southern bight of the North Sea.** *Atmospheric Environ*. Part A, General Topics [Internet]. 1992 May [cited 2016 May 12];7(26):1231-37. Available from: http://www.sciencedirect.com/science/article/pii/096016869290384W Subscription required to view.

56. **Marcazzan GM, Vaccaro S, Valli G, Vecchi R**. **Characterization of PM_{10} and $PM_{2.5}$ particulate matter in the ambient air of Milan** (Italy). *Atmospheric Environ* [Internet]. 2001 Sep [cited 2016 May 12];35(27):4639-50. Available from: http://www.freepaperdownload.us/1750/Article7668923.htm Subscription required to view.

57. **Bocca B, Caimi S, Smichowski P, Gomez D, Caroli S**. **Monitoring Pt and Rh in urban aerosols from Buenos Aires, Argentina.** *Sci Total Environ* [Internet]. 2006 Apr 1 [cited 2016 May 12];358(1-3):255-64. Available from: http://www.sciencedirect.com/science/article/pii/S0048969705002603 Subscription required to view.

58. **Gomez DR, Gine MF, Sanchez-Bellato AC, Smichowski P**. **Antimony: a traffic-related element in the**

atmosphere of Buenos Aires, Argentina. J Environ Monit [Internet]. 2005 Dec [cited 2016 May 12];7(12):1162-8. Available from: http://pubs.rsc.org/en/Content/ArticleLanding/2005/EM/b508609d#!divAbstract Subscription required to view.

59. **Smichowski P, Gomez DR, Dawidowski LE, Gine MF, Bellato AC, Reich SL**. **Monitoring trace metals in urban aerosols from Buenos Aires city. Determination by plasma-based techniques.** *J Environ Monit* [Internet]. 2004 Apr [cited 2016 May 12];6(4):286-94. Available from: http://pubs.rsc.org/en/Content/ArticleLanding/2004/EM/B312446K#!divAbstract Subscription required to view.

60. **Sanchez-Rodas D, Sanchez de la Campa AM, de la Rosa JD, Oliveira V, Gomez-Ariza JL, Querol X, Alastuey A.** **Arsenic speciation of atmospheric particulate matter (PM_{10}) in an industrialised urban site in southwestern Spain. Chemosphere** [Internet]. 2007 Jan [cited 2016 May 12];66(8):1485-93. Available from: http://www.sciencedirect.com/science/article/pii/S0045653506011842 Subscription required to view.

61. **Chow JC, Watson JG**. **Western Washington 1996-97 $PM_{2.5}$ source apportionment study.** Seattle, Washington: Puget Sound Air Pollution Control Agency; 1998. Report No.: 98-01.

62. **Borbely-Kiss I, Koltay E, Szabo GY, Bozo L, Tar K**. **Composition and sources of urban and rural atmospheric aerosol in eastern Hungary.** *J Aerosol Sci* [Internet]. 1999 Mar [cited 2016 May 12];30(3):369-91. Available from: http://www.sciencedirect.com/science/article/pii/S0021850298000512 Subscription required to view.

63. **WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: global update 2005** [Internet]. Geneva, Switzerland: World Health Organization; 2006 [cited 2016 May 12]. 20 p. Available from: http://apps.who.int/iris/bitstream/10665/69477/1/WHO_SDE_PHE_OEH_06.02_eng.pdf

64. **Chaloulakou A, Kassomenos P, Spyrellis N, Demokritou P, Koutrakis P**. Measurements of PM_{10} **and $PM_{2.5}$ particle concentrations in Athens, Greece.** *Atmospheric Environ* [Internet]. 2003 Feb [cited 2016 May 12];37(5):649-60. Available from: http://www.sciencedirect.com/science/article/pii/S1352231002008981 Subscription required to view.

65. **Peled R, Friger M, Bolotin A, Bibi H, Epstein L, Pilpel D, Scharf S**. **Fine particles and meteorological conditions are associated with lung function in children with asthma living near two power plants.** *Public Health* [Internet]. 2005 May [cited 2016 May 12];119(5):418-25. Available from: http://www.sciencedirect.com/science/article/pii/S0033350604001805 Subscription required to view.

66. **Abu-Allaban M, Lowenthal DH, Gertler AW, Labib M**. **Sources of PM_{10} and $PM_{2.5}$ in Cairo's ambient air.** *Environ Monit Assess* [Internet]. 2007 Oct [cited 2016 May 12];133(1):417–25. Available from: http://link.springer.com/article/10.1007/s10661-006-9596-8 Subscription required to view.

67. **Kocak M, Kubilay N, Herut B, Nimmo M**. **Trace metal solid state speciation in aerosols of the northern Levantine Basin, East Mediterranean.** *J Atmospheric Chem* [Internet]. 2007 Apr [cited 2016 May 12];56(3):239-57. Available from: http://link.springer.com/article/10.1007%2Fs10874-006-9053-7 Subscription required to view

68. **Pey J, Rodriguez S, Querol X, Alastuey A, Moreno T, Putaud JP, Van Dingenen R**. **Variations of urban aerosols in the western Mediterranean.** *Atmospheric Environ* [Internet]. 2008 Dec [cited 2016 May 12];42(40):9052-62. Available from: http://www.sciencedirect.com/science/article/pii/S1352231008008467 Subscription required to view.

69. **Saliba NA, El Jam F, El Tayar G, Obeid W, Roumie M**. **Origin and variability of particulate matter (PM_{10} and $PM_{2.5}$) mass concentrations over an Eastern Mediterranean city.** *Atmospheric Res* [Internet]. 2010 Jun [cited 2016 May 12];97(1-2):106-14. Available from: http://www.sciencedirect.com/science/article/pii/S0169809510000608 Subscription required to view.

70. **Tahri M, Bounakhla M, Zghaid M, Noack Y, Benyaich F, Benchrif A.** **Evaluation of airborne particulate matter pollution in Kenitra City, Morocco.** *Ambiente Agua Interdiscip J Appl Sci* [Internet]. 2013 Apr [cited 2016 May 12];8(1):38–47. Available from: http://www.scielo.br/pdf/ambiagua/v8n1/04.pdf

71. **Hansen J, Sato M, Ruedy R**. **Radiactive forcing and climate response.** *J Geophys Res* [Internet]. 1997 Mar 27 [cited 2016 May 12];102(D6):6831-64. Available from: http://onlinelibrary.wiley.com/doi/10.1029/96JD03436/epdf

72. **Ackerman AS, Toon OB, Stevens DE, Heymsfield AJ, Ramanathan V, Welton EJ**. **Reduction of tropical cloudiness by soot.** *Sci* [Internet]. 2000 May 12 [cited 2016 May 12];288(5468):1042-47. Available from: http://science.sciencemag.org/content/288/5468/1042 Subscription required to view.

73. **Kahn RA, Yu H, Schwartz SE, Chin M, Feingold G, Remer LA, Rind D, Halthore R, DeCola P**. **Introduction.** In: Chin M, Kahn RA, Schwartz SE, editors. *Atmospheric aerosol properties and climate impacts* [Internet]. Washington D.C.: United States Climate Change Science Program; 2009 Jan [cited 2016 May 12]. Chapter 1. Available from: http://www.geoengineeringwatch.org/documents/atmospheric-aerosol-properties-and-climate-impacts.pdf

74. **Koren I, Kaufman YJ, Remer LA, Martins JV.** **Measurement of the effect of Amazon smoke on inhibition of cloud formation.** *Sci* [Internet]. 2004 Feb 27 [cited 2016 May 12];303(5662):1342-5. Available from: http://science.sciencemag.org/content/303/5662/1342 Subscription required to view.

75. **Koren I, Kaufman YJ, Rosenfield D, Remer LA, Rudich Y**. **Aerosol invigoration and restructuring of Atlantic convective clouds.** *Geophys Res Lett* [Internet]. 2005 Jul 28 [cited 2016 May 12];32(14):1-4. Available from: http://onlinelibrary.wiley.com/store/10.1029/2005GL023187/asset/grl19992.pdf?v=1&t=io4tcuxo&s=725040c54370a6841a844eca1617651618121852&systemMessage=Wiley+Online+Library+will+be+unavailable+on+Saturday+14th+May+11%3A00-14%3A00+BST+%2F+06%3A00-09%3A00+EDT+%2F+18%3A00-21%3A00+SGT+for+essential+maintenance.Apologies+for+the+inconvenience

76. **Kaufman YJ, Koren I, Remer LA, Rosenfield D, Rudich Y**. **The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean.** *Proc Natl Acad Sci* [Internet]. 2005 Aug 9 [cited 2016 May 12];102(32):11207-12. Available from: http://www.pnas.org/content/102/32/11207.full.pdf

77. **Matheson MA, Coakley JA, Tahnk WR**. **Aerosol and cloud property relationships for summertime stratiform clouds in the Northeastern Atlantic from advanced very high resolution radiometer observations.** *J Geophy Res* [Internet]. 2005 Dec 23 [cited 2016 May 12];110(D24204):1-16. Available from: http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/15107/Matheson%20et%20al%20JGR%202005.pdf?sequence=1

78. **Sekiguchi, M, Nakajima T, Suzuki K, Kawamoto K, Higurashi A, Rosenfeld D, Sano I, Mukai S**. **A study of the direct and indirect effects of aerosols using global satellite data sets of aerosol and cloud parameters.** *J Geophys Res* [Internet]. 2003 Nov 21[cited 2016 May 12];108(D22). Available from: http://onlinelibrary.wiley.com/doi/10.1029/2002JD003359/full

79. **Yu H, Fu R, Dickinson RE, Zhang Y, Chen M, Wang H.** **Interannual variability of smoke and warm cloud relationships in the Amazon as inferred from MODIS retrievals.** *Remote Sens Environ* [Internet]. 2007 Dec 21 [cited 2016 May 12];111(4):435-49. Available from: http://www.sciencedirect.com/science/article/pii/S0034425707001502 Subscription required to view.

80. **Ambient (outdoor) air pollution in cities database 2014** [Internet]. Geneva, Switzerland: World Health Organization; 2014 [cited 2016 May 12]. [about 3 screens]. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/cities-2014/en/